Infall models of elliptical galaxies: further evidence for a top-heavy initial mass function

B.K. Gibson[1] & F. Matteucci[2]

[1] *Mount Stromlo & Siding Spring Observatories, Australian National University, Weston Creek P.O., Weston, ACT, Australia 2611*
[2] *Scuola Internazionale Superiore di Studi Avanzati, Via Beirut 2-4, Trieste, Italy 34013*

1 February 2008

ABSTRACT
Chemical and photometric models of elliptical galaxies with infall of primordial gas, and subsequent ejection of processed material via galactic winds, are described. Ensuring that these models are consistent with the present-day colour-luminosity relation *and* the measured intracluster medium (ICM) abundances, we demonstrate that the initial mass function (IMF) must be significantly flatter (i.e. $x \approx 0.80$) than the canonical Salpeter slope (i.e. $x \approx 1.35$). Such a "top-heavy" IMF is in agreement with the earlier conclusions based upon closed-box models for elliptical galaxy evolution. On the other hand, the top-heavy IMF, in conjunction with these semi-analytic infall models, predicts an ICM gas mass which exceeds that observed by up to a factor three, in contrast with the canonical closed-box models. Time and position-dependent IMF formalisms *may* prove to be a fruitful avenue for future research, but those presently available in the literature are shown to be inconsistent with several important observational constraints.

Key words: galaxies: abundances - galaxies: elliptical - galaxies: evolution - galaxies: intergalactic medium

1 INTRODUCTION

Supernovae (SNe)-driven winds, and in particular their role in setting the timescale for the cessation of bulk star formation, have long been recognised as important components of elliptical galaxy formation/evolution models. Such wind models provide a natural framework in which the intrinsic elliptical galaxy colour-metallicity-luminosity (CML) relationships can be established (e.g. Larson 1974; Arimoto & Yoshii 1987; Gibson 1996a,b). An inescapable consequence of such SNe-driven winds is the enrichment of the intergalactic medium with the products of SNe nucleosynthesis (e.g. Larson & Dinerstein 1975).

Such wind "pollution" is particularly evident in the hot intracluster medium (ICM) of elliptical-rich galaxy clusters. Early, Type II SNe-dominated winds are the favoured mechanism at play here, as evidenced by the strong α-element enhancement signatures in this hot gas (e.g. [O/Fe]$\gtrsim$ +0.2 – Mushotzky et al. 1996). The absolute mass of iron in a cluster's ICM can be shown to be related to the host cluster's integrated V-band luminosity tied up in ellipticals; i.e.

$$M_{\mathrm{Fe}}^{\mathrm{ICM}} \approx 0.02 L_{\mathrm{V}}^{\mathrm{E}}, \qquad (1)$$

where the mass and luminosity are in solar units (Arnaud 1994). Similarly, a cluster's ICM gas mass $M_{\mathrm{g}}^{\mathrm{ICM}}$ can be related to its early-type galaxy V-band luminosity by

$$M_{\mathrm{g}}^{\mathrm{ICM}} \approx 20 \to 50 L_{\mathrm{V}}^{\mathrm{E}}, \qquad (2)$$

with loose groups and rich clusters populating the low and high luminosity extrema, respectively. While important,[⋆] these ICM constraints do not, by themselves, provide much information on the underlying star formation or initial mass function (IMF) formalisms.

Previous papers in this series (Matteucci & Gibson 1995; Gibson & Matteucci 1997) have adopted the classic *closed-box model* for a galaxy's evolution and concluded that IMFs significantly flatter-than-Salpeter's (1955) canonical power-law slope $x = 1.35$ are required, in order to fit the ICM constraints noted above. Similar conclusions have been drawn by David, Forman & Jones (1991) Zepf & Silk (1996) and Loewenstein & Mushotzky (1996).

In the past year though, interest has been piqued by the adoption of gas *infall* models for ellipticals (e.g. Tantalo et al. 1996; Kodama & Arimoto 1997), in lieu of the aforementioned closed-box scenarios. Such studies retain the SNe-driven wind framework but consciously restrict themselves to the spectrophotometric properties of their model galaxies, neglecting the consequences for enriching the ICM. Because

---

[⋆] For example, because of the α-element overabundance signature, late-time Type Ia SNe-driven wind models are no longer a viable *dominant* ICM-pollution mechanism.

there exists a level of degeneracy in the present-day CML relationships, due to uncertainties in the IMF (e.g. Table 8 of Gibson 1997), star formation methodology, SNe energetics, etc, Tantalo et al. and Kodama & Arimoto used, partially for convenience, IMF power law slopes close to the Salpeter (1955) value – the former, $x = 1.35$; the latter, $x = 1.20$.

The time is now ripe to assess the infall model in light of the heretofore neglected ICM constraints – in particular, the abundance ratios and absolute gas masses – in order to better appreciate its strengths and weaknesses. What follows represents the first application of gas infall models to the ICM constraints, with answering the question – *in the presence of gas infall, is the IMF in cluster ellipticals dominated by high-mass stars (*i.e. *top-heavy), or does it follow the more canonical Salpeter distribution?* – being the highest priority.

To this end, in Section 2 we remind the reader of the primary motivation for considering the infall model in the first place. Following this, in Section 3, we present a grid of models which parallels that of Kodama & Arimoto (1997). We follow their numerical formalism, for convenience sake, although its similarity to that of Tantalo et al. 's (1996) means our conclusions are independent of this choice. As we will show, the favoured Kodama & Arimoto grid, with IMF slope $x \approx 1.2$, underproduces ICM iron by approximately a factor of five. We next present an alternate grid of infall models consistent with the ICM abundance constraints. As discussed in Section 3, consistent with the results of earlier closed-box models, only IMF slopes significantly flatter-then-Salpeter (i.e. $x \lesssim 0.8$) were capable of recovering the galaxy CML relations *and* the ICM abundance constraints, albeit at the expense of the ICM gas mass constraint. Our results are summarised in Section 4.

2   WHY INFALL MODELS?

Recall that our earlier papers (Matteucci & Gibson 1995; Gibson & Matteucci 1997) adopted the straightforward closed-box model for galaxy evolution. In particular, the star formation rate ψ was assumed to vary directly with the gas mass, as

$$\psi(t) = \nu M_{\mathrm{g}}(t), \tag{3}$$

with the timescale for star formation ν varying in such a way that the present-day CML relations were properly established. In the closed-box model, star formation is a maximum at $t = 0$, steadily decreasing thereafter. Gibson & Matteucci (1997) showed that one can successfully recover the $[(V-K),L_{V}]$ relation for ellipticals, and still honour all of the ICM abundance constraints, within the closed-box model framework, *but* only for IMF slopes significantly flatter-than-Salpeter's (1955) – e.g. a slope $x \approx 1$, as opposed to Salpeter's canonical $x = 1.35$, was necessary.

It has since become apparent (e.g. Tantalo et al. 1996; Kodama & Arimoto 1997) though that this same closed-box model for ellipticals does not appear to have the same success in recovering the *ultraviolet (UV)-optical* CML relations, a point not explored in the Gibson & Matteucci (1997) study. The reason for this failure is the overproduction of low-metallicity (i.e. Z=0) stars during the initial intense star formation regime; the signature of such a component is not seen in the integrated spectra of old stellar populations (Worthey, Dorman & Jones 1996).

Several alternate star formation formalisms, aimed specifically at avoiding this low-metallicity overproduction, have since been published – the previously noted Tantalo et al. (1996) and Kodama & Arimoto (1997) studies being the most noteworthy. These infall models are similar in spirit to those designed to avoid the analogous G-dwarf problem encountered by solar neighbourhood-enrichment models (e.g. Tinsley 1980), although for ellipticals, the infall timescales are, of course, substantially different to the slower accretion rates expected for spirals. Following Tantalo et al. and Kodama & Arimoto, we adopt an infall rate which parallels the free-fall timescale. Star formation, in both models, is assumed to follow equation 3, but instead, with an initial gas mass of zero, increasing in accordance with the assumed gas infall rate law. The accompanying rapid increase in global metallicity means that very few low-metallicity stars are formed, avoiding the G-dwarf problem.

In summary, gas infall models for elliptical galaxies have been considered as viable alternatives to the classic closed-box model, primarily because they provide a simple solution to the overproduction of low metallicity stars which plagues the closed-box models - such a G-dwarf problem manifests itself most clearly in the closed-box model's problem in recovering the UV-optical CML relations.

3   ANALYSIS

3.1   The models

Using the photo-chemical evolution code of Gibson (1996a,b;1997), we constructed a grid of seven elliptical galaxy models consistent with the "metallicity sequence" of Kodama & Arimoto (1997, hereafter KA97). In particular, KA97 adopted an IMF slope mildly flatter (i.e. $x = 1.20$) than Salpeter's (1955) $x = 1.35$, with a mass range of $0.1 \rightarrow 60.0$ M$_{\odot}$. The cessation of star formation (i.e. at time t_{GW}) was treated as a free parameter, and varied to ensure recovery of the present-day elliptical galaxy CML relations.[†] Reasonable values for the parameters governing the timescales for star formation and gas infall were adopted (i.e. 0.1 Gyr), independent of galaxy model. The adopted nucleosynthetic yields are described in Gibson & Mould (1997).

The first block of models in Table 1 represent our pseudo-KA97 grid (i.e. those labelled $x = 1.20$); unlike the data presented in their Table 2, to which the reader is referred for additional parameters not relevant to the discussion at hand, we have included the masses of gas, oxygen, and iron ejected to the ICM, for each model (in units of 10^{9} M$_{\odot}$, 10^{6} M$_{\odot}$, and 10^{6} M$_{\odot}$, respectively). The initial

---

[†] It should be noted that KA97's models are systematically redder in (V-K) than ours, by ~ 0.06 mag. Tracing the source of this discrepancy is not possible at this time, as their simple stellar population (SSP) colours are not currently available. Our grid is based upon the published Bertelli et al. (1994) isochrones, with the low mass extensions outlined in Gibson (1996a). For the alternate grid of models to be discussed shortly, we ensure self-consistency by maintaining this systematic 0.06 magnitude offset in (V-K).
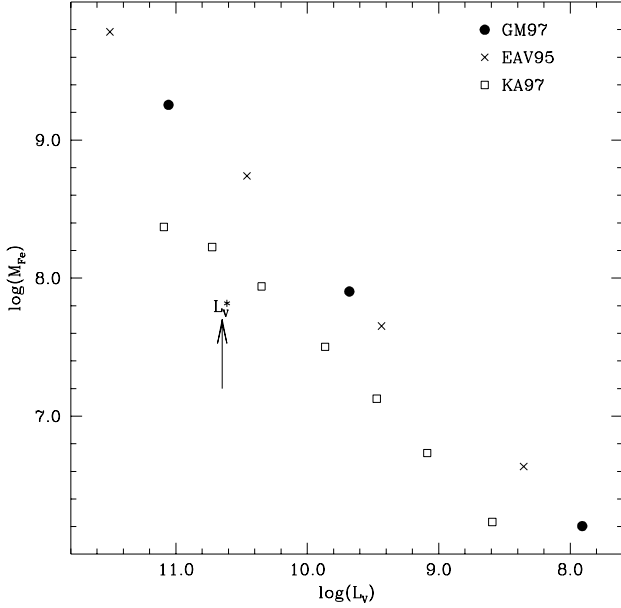
Figure 1. Mass of iron ejected to the ICM as a function of present-day V-band luminosity. The models of Gibson & Matteucci (1997, GM97), Elbaz et al. (1995, EAV95), and Kodama & Arimoto (1997, KA97) are shown. The characteristic cluster galaxy V-band luminosity L_V^* is indicated.

Figure 2. Evolution of the star formation rate ψ as a function of time t, for the seven "metallicity-sequence" models of Kodama & Arimoto (1997), with IMF slope $x = 1.20$ (solid curve). Also shown are the parallel grid of models with slope $x = 0.80$ (dotted curve), constructed *a posteriori* to recover Arnaud's (1994) cluster luminosity-ICM iron mass relation. The galactic mass of the respective models decreases from top-to-bottom, as per the corresponding entries in Table 1.

gas mass reservoir associated with each model (i.e. M_T, in units of 10^9 $M_\odot$) is also provided in column 2, as it was not included in KA97's Table 2. Column 7 shows the residual reservoir gas mass at the time of galactic gas expulsion t_{GW}, again in units of 10^9 $M_\odot$.

Of immediate concern is the mass of iron ejected from each of the model galaxies (column 6 of Table 1). In Figure 1 we show this mass of iron M_{Fe}, for the Kodama & Arimoto (1997) models of Table 1, as a function of the present-day V-band luminosity (open squares). For comparison, the predictions of Gibson & Matteucci (1997, their "standard model") and Elbaz, Arnaud & Vangioni-Flam (1995) are also shown, with filled circles and crosses, respectively. We stress that the latter two models have been specifically designed to honour Arnaud's (1994) cluster V-band luminosity–ICM iron mass relation (equation 1).[‡] It should be readily apparent from Figure 1 that Kodama & Arimoto's models systematically underproduce (by a factor of ~ 5) the necessary iron to recover Arnaud's relationship (equation 1).

3.2 Infall and the IMF

Our next step was to investigate mechanisms whereby Arnaud's (1994) relationship *could* be honoured, but from within the infall framework. Varying the timescale for star formation, the gas infall rate, or the yield selection, does not alter the conclusion of the previous paragraph – i.e. the

models still underproduce iron.[§] *The only ingredient which could be varied, and recover the M_{Fe}^{ICM}–L_V^E relationship successfully, was the IMF slope.*[¶]

Keeping all other input parameters the same as for the $x = 1.20$ grid of models, we varied the IMF slope x and the initial gas reservoir mass M_T, until a grid was generated which honoured Arnaud's (1994) $M_{Fe}^{ICM} - L_V^E$ relationship (equation 1) *and* retained consistency with the elliptical galaxy [(V-K),L_V] relation. An IMF slope $x = 0.80$ was found to be necessary, in order to recover the mean of this relationship. A subset of these models are shown in the second block of Table 1. The galactic wind epochs for these models ranged from 120 to 65 Myrs (from most to least luminous). For comparison, Figure 2 shows how the star formation rate evolves for this subset (dotted curves), as well as those for the standard $x = 1.20$ models (solid curves) of Table 1.

3.3 Potential problems with the infall scenario

Besides our conclusion regarding the necessarily steeper-than-Salpeter (1955) IMF slope of $x \approx 0.80$, there are two

---

[‡] While it is true that both Gibson & Matteucci's (1997) and Elbaz et al. 's (1995) models obey equation 1, only the former is consistent with the optical-infrared elliptical galaxy CML relations (Gibson 1996a).
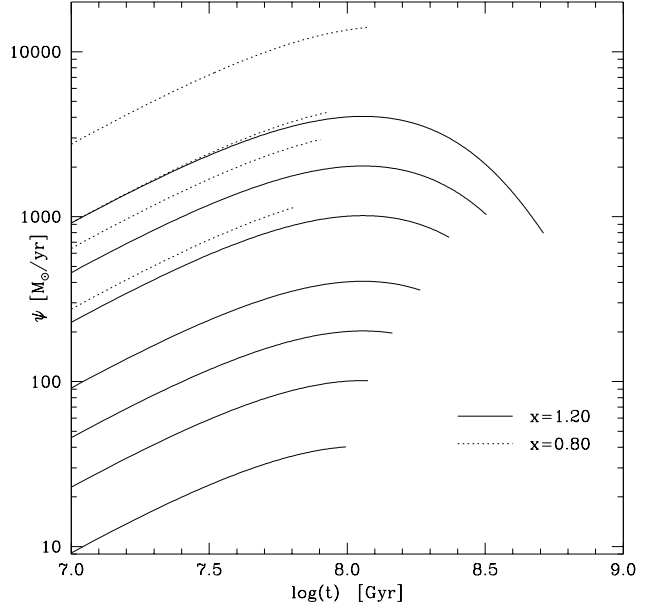
[§] Invoking a later-time Type Ia SNe-driven wind component of such magnitude as to fully recover the ICM iron mass-cluster V-band luminosity relationship (equation 1), drives the predicted ICM [O/Fe] to ~ -0.5, a factor of $\sim 5 \rightarrow 10\times$ lower than observed (Mushotzky et al. 1996).

[¶] Bimodal IMFs are also a possibility, but in their simplest form (Elbaz et al. 1995) do not recover the observed CML relations (Gibson 1996a).

[hpt]

Table 1. Elliptical galaxy models constructed to conform to the *metallicity sequence* of Kodama & Arimoto (1997) – i.e. the block containing models with an IMF slope $x = 1.20$. The second block of models (i.e. IMF slope $x = 0.80$) was constructed *a posteriori* to ensure compatibility with Arnaud's (1994) cluster V-band luminosity-ICM iron mass relationship (equation 1). The masses of gas, oxygen, and iron ejected at time to the ICM (columns 4, 5, and 6) at time t_{GW} are in units of 10^9 M$_\odot$, 10^6 M$_\odot$, and 10^6 M$_\odot$, respectively. Column 7 is the mass of gas remaining in the initial reservoir at time t_{GW}, also in units of 10^9 M$_\odot$. See text for details.

M_V	M_T	$[<Z>]_V$	$M_g(t_{GW})$	$M_O(t_{GW})$	$M_{Fe}(t_{GW})$	$M_g^{res}(t_{GW})$
			$x = 1.20$			
-22.91	1000	+0.16	79	2832	218	9
-21.99	500	-0.06	102	2508	168	20
-21.05	250	-0.19	75	1369	87	24
-19.84	100	-0.32	36	516	32	16
-18.86	50	-0.44	20	224	13	12
-17.90	25	-0.53	10	93	5	8
-16.66	10	-0.64	4	30	2	4
			$x = 0.80$			
-22.44	3000	-0.12	1404	34660	1725	904
-20.78	1000	-0.31	427	7353	336	427
-20.32	700	-0.34	294	4789	216	311
-19.08	300	-0.48	114	1439	61	157

other points which should be drawn from the model grid of Table 1.[||] First, the standard $x = 1.20$ grid *already* lies consistently $\sim 0.1 \to 0.3$ dex below the mean observed $\left[[<Z>]_V, M_V\right]$ relation (e.g. see Figure 1 of Gibson & Matteucci 1997). The new $x = 0.80$ grid, which is now consistent with the ICM constraint of equation 1, only exacerbates this shortcoming, being a *further* ~ 0.1 dex removed from the mean. Second, and perhaps more importantly, the flatter IMF grid requires an initial gas mass reservoir $\sim 5\times$ more massive than that for the steeper IMF grid, for galactic models of the same present-day luminosity.

Following Section 7 of Elbaz et al. (1995), we then use the models of Table 1 to find that the *predicted* ICM gas mass to cluster luminosity is

$$M_T^{ICM} \approx 8L_V^E, \tag{4}$$

for the $x = 1.20$ grid, and

$$M_T^{ICM} \approx 55L_V^E, \tag{5}$$

for the $x = 0.80$ grid. This predicted ICM gas mass includes the mass of gas ejected at t_{GW} (column 4 of Table 1) and the residual, unincorporated, reservoir gas (column 7). An additional component from late-time (i.e. $t > t_{GW}$) winds or ram pressure stripping can be included but does not alter the coefficients shown in equations 4 and 5. The coefficients can be reduced by a factor of ~ 2 to recover the relation based upon the ejected gas mass at t_{GW} alone.

For the $x = 1.20$ IMF, equation 4 implies that $\sim 40 \to 15\%$ (loose groups to rich clusters) of the total ICM gas (i.e. equation 2) has been accounted for; $\sim 60\%$ of this has been processed and ejected from cluster ellipticals, and $\sim 40\%$ is associated with residual reservoir-gas. [★★] The remaining

$\sim 60 \to 85\%$ (loose groups to rich clusters) of the observed ICM gas must therefore be assigned to some gas component which simply does not partake in the star formation process (either "actively" through galactic wind ejection, or "passively", by being associated with a specific galactic halo's initial gas reservoir). This is perfectly in keeping with the results of Matteucci & Vettolani (1988), David et al. (1991), Elbaz et al. (1995), and Gibson & Matteucci (1997).

On the other hand, equation 5, coupled with the $x = 0.80$ grid, implies that $\sim 300 \to 100\%$ (again, loose groups to rich clusters) of the total ICM gas (i.e. equation 2) has been accounted for! Again, this gas can be considered to be $\sim 50\%$ "processed-and-ejected" and $\sim 50\%$ "initial gas reservoir-associated" – no other cluster gas constituent need be invoked. The problem lies, of course, in that for any system "poorer" than the richest clusters, there is an accompanying overproduction of gas – i.e. *the grid of infall models constructed with the most conservative input parameters require, and yield, more gas than is actually observed, for all but the richest clusters.* Some of this discrepancy may be alleviated if the galactic winds are successful in overcoming not only an individual galaxy's potential well, but that of the group's as well, dispersing some fraction of the "excess" gas to the general intergalactic medium.

3.4 Variable IMFs?

Because of the closed-box model's failure to properly recover the UV-optical CML relations (recall Section 2) and the infall model's problems with gas "overproduction", it might be tempting, by process of elimination, to support the notion of time (and position)-variable IMFs, a là Padoan, Nordlund & Jones (1997). Detailed models based upon Padoan et al. 's "universal" IMF formalism will be presented elsewhere, but we would be remiss if we did not at least temper

---

[||] The mass-to-blue light ratios (M/L$_B$) for the $x = 0.80$ models are $\sim 10 \to 15\%$ lower than the corresponding $x = 1.20$ grid. While interesting, the uncertainties in deriving the observational M/L$_B$–L$_B$ relation make any further discussion regarding this difference moot.

[★★] These percentages have associated errors of $\sim 20\%$, as we have fit simple power-laws to the gas mass–cluster luminosity

relations in order to follow the procedure laid out in Section 7 of Elbaz et al. (1995). Strictly, a numerical integration should be performed, as discussed already in Gibson & Matteucci (1997), but for simplicity's sake we adhere to the Elbaz et al. formalism.

such "default" support, by noting two of the weaknesses in the (currently) best available variable-IMF elliptical galaxy models.

Chiosi & Bressan (1997) have presented their first (preliminary) grid of elliptical galaxy models, based upon the Padoan et al. (1997) variable-IMF formalism. These models were designed primarily to satisfy one projection of the fundamental plane (specifically, M/L_B versus M_B), while still retaining consistency with the underlying galaxy CML relations and observed α-element *stellar population* overabundance. While successful in satisfying these constraints, there are two equally important observational constraints which are clearly violated.

First, local dwarf ellipticals such as Fornax, NGC 185, and NGC 205, each host populations of planetary nebulae with [O/Fe] typically $\sim +0.2$, and ages presumably on the order of several Gyrs (Richer, McCall & Arimoto 1997). An inescapable result of the Chiosi & Bressan (1997) "canonical" dwarf elliptical (dE) model (see their Figure 2) is that dE planetary nebulae, of this typical age, should have [O/Fe] of $\lesssim -1.4$, a factor of ~ 40 lower than that observed.

Second, and perhaps more important, is the predicted ICM [O/Fe] from the Chiosi & Bressan (1997) grid. As their dwarf ellipticals never develop galactic winds, it is really only the $\sim L_*$ galaxies which can contribute to the observed [O/Fe]$\gtrsim +0.2$ (Mushotzky et al. 1996). Again, referring to their Figure 1, we can see that their $\sim L_*$ ellipticals develop galactic winds after ~ 3.5 Gyrs, by which point the ISM [O/Fe] has been reduced to ~ -1 (their Figure 2). *This factor of $\sim 10 \rightarrow 20$ discrepancy between observed and theoretical ICM [O/Fe] points to a significant deficiency in the existing elliptical galaxy variable-IMF models.*

Third, the Chiosi & Bressan (1997) $\sim L_*$ model (again, coupling their Figure 1 with the adopted star formation formalism) shows star formation rate, in the core alone (where $\lesssim 10\%$ of the galaxy's luminous mass lies), ranging from $\psi \sim 6000 \rightarrow 1500$ M$_\odot$/yr from redshifts of ~ 5 to ~ 1. The total *global* star formation rate is $\sim 2 \rightarrow 3\times$ this *core* value. Such star formation rates at $z \sim 1$ (i.e. $\psi \gtrsim 3000$ M$_\odot$), regardless of IMF, are clearly at odds with the cosmological number counts (e.g. Charlot & Silk 1995), although a more formal analysis, in a cosmological context, is postponed for the time being.

To end on a positive note though, the above arguments do not necessarily preclude the possibility that future, more sophisticated, variable-IMF models, may reconcile *all* of the galaxy CML relations *and* ICM constraints. It should be reiterated that the Chiosi & Bressan (1997) results are still preliminary, and that the full parameter space still needs to be explored. What is clear though, is that the models presented *thus far* are not necessarily the panacea they might at first appear to be.

4 SUMMARY

We have constructed a grid of gas infall models of elliptical galaxies, based upon the favoured sequence of Kodama & Arimoto (1997). For an IMF power-law slope $x = 1.20$, the models are entirely consistent with the observed, present-day, colour-luminosity relations for cluster ellipticals. While previous closed-box models were equally successful in recov-

ering the optical-infrared relations, the infall models do have the advantage of a better fit to the ultraviolet-optical relations (albeit, at the expense of a poorer fit to the metallicity-luminosity relation). We assess qualitatively the ability of Padoan et al. 's (1997) variable-IMF scenario, as adopted by Chiosi & Bressan (1997), to circumvent the closed-box/infall "problems", and conclude that the extent models admittedly minimise some of these problems, *but* only at the expense of introducing new ones.

For the first time, we have employed infall models as input to simple cluster enrichment scenarios. For the published grids, which appear to favour IMF slopes similar to that of the canonical Salpeter (1955) value (i.e. $x \approx 1.2 \rightarrow 1.4$), an inescapable conclusion is that the predicted mass of iron ejected to a cluster's ICM is a factor of ~ 5 below that observed. Only by substantially "flattening" the IMF (to $x \approx 0.8$), were we able to construct an "infall" grid which was consistent with *both* the galactic colour-luminosity relations and ICM iron mass-cluster luminosity relation, albeit at (a) the expense of modestly worsening the galactic metallicity-luminosity relation, and (b) overproducing ICM gas for all but the richest clusters. This latter point may be indicative of a fundamental flaw in the infall picture, but we prefer to reserve judgment on this point until more sophisticated models have been explored.

In the meantime though, we are able to conclude that, by adopting an already accepted (e.g. Tantalo et al. 1996; Kodama & Arimoto 1997) formalism for elliptical galaxy evolution based upon gas infall, the IMF must necessarily favour the formation of massive stars (i.e. be "top-heavy") if the models are to conform to the present-day CML relations, as well as the ICM abundance constraints. This agrees with our earlier studies based upon the more conventional closed-box model (Matteucci & Gibson 1995; Gibson & Matteucci 1997). It is encouraging that two such disparate approaches (i.e. closed-box versus infall) to modeling the evolution of ellipticals *both* lead to the same conclusion regarding the veracity of the top-heavy IMF hypothesis.

REFERENCES

Arimoto, N. & Yoshii, Y. 1987, A&A, 173, 23
Arnaud, M. 1994, Clusters of Galaxies, ed. F. Durret, A. Mazure & J. Tran Thanh Van, Gif-sur-Yvette: Editions Frontieres, 211
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F. & Nasi, E. 1994, A&AS, 106, 275
Charlot, S. & Silk, J. 1995, ApJ, 445, 124
Chiosi, C. & Bressan, A. 1997, Galaxy Scaling Relations: Origins, Evolution and Applications, ed. da Costa, L. et al. , in press
David, L.P., Forman, W. & Jones, C. 1991, ApJ, 380, 39
Elbaz, D., Arnaud, M. & Vangioni-Flam, E. 1995, A&A, 303, 345
Gibson, B.K. 1996a, MNRAS, 278, 829
Gibson, B.K. 1996b, ApJ, 468, 167
Gibson, B.K. 1997, MNRAS, in press
Gibson, B.K. & Matteucci, F. 1997, ApJ, 475, 47

Gibson, B.K. & Mould, J.R. 1997, ApJ, 482, 98

Kodama, T. & Arimoto, N. 1997, A&A, 320, 41

Larson, R.B. 1974, MNRAS, 169, 229

Larson, R.B. & Dinerstein, H.L. 1975, PASP, 87, 911

Loewenstein, M. & Mushotzky, R.F. 1996, ApJ, 466, 695

Matteucci, F. & Gibson, B.K. 1995, A&A, 304, 11

Matteucci, F. & Vettolani, G. 1988, A&A, 202, 21

Mushotzky, R., Loewenstein, M., Arnaud, K.A., Tamura, T., Fukazawa, Y., Matsushita, K., Kikuchi, K. & Hatsukade, I. 1996, ApJ, 466, 686

Padoan, P., Nordlund, A.P. & Jones, B.J.T. 1997, MNRAS, 288, 145

Salpeter, E.E. 1955, ApJ, 121, 161

Tantalo, R., Chiosi, C., Bressan, A. & Fagotto, F. 1996, A&A, 311, 361

Tinsley, B.M. 1980, Fund. Cosm. Phys., 5, 287

Worthey, G., Dorman, B & Jones, L.A. 1996, AJ, 112, 948

Zepf, S.E. & Silk, J. 1996, ApJ, 466, 114